Quasi-regular X-ray bursts from GRS 1915+105 observed with the IXAE: possible evidence for matter disappearing into the event horizon of the black hole

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ABSTRACT

Three different types of very intense, quasi-regular X-ray bursts have been observed from the Galactic superluminal X-ray transient source GRS 1915+105 with the Pointed Proportional Counters of the Indian X-ray Astronomy Experiment onboard the Indian satellite IRS-P3. The observations were carried out from 1997 June 12 to June 29 in the energy range of 2−18 keV and revealed the presence of persistent quasi-regular bursts with different structures. Only one of the three types of bursts is regular in occurrence revealing a stable profile over extended durations. The regular bursts have an exponential rise with a time scale of about 7 to 10 s and a sharp linear decay in 2 to 3 s. The X-ray spectrum becomes progressively harder as the burst evolves and it is the hardest near the end of the burst decay. The profile and energetics of the bursts in this black hole candidate source are distinct from both the type I and type II X-ray bursts observed in neutron star sources. We propose that the sharp decay in the observed burst pattern is a signature of the disappearance of matter through the black hole horizon. The regular pattern of the bursts can be produced by material influx into the inner disk due to oscillations in a shock front far away from the compact object.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — X-rays: bursts, stars — stars: individual GRS 1915+105

1. Introduction

The X-ray transient source GRS 1915+105 was discovered in 1992 with the WATCH all sky X-ray monitor onboard the GRANAT satellite (Castro-Tirado et al. 1994). During the two years of hard X-ray observations by WATCH, two powerful outbursts were discovered and during the peak of the outbursts the source luminosity was as high as 10^{39} erg s^{-1}. Superluminal motions of two symmetric radio emitting jets of GRS 1915+105 were discovered by Mirabel & Rodriguez (1994). Correlated enhanced radio and X-ray emissions were discovered from the source with a near simultaneous monitoring over a long period (Foster et al. 1996; Harmon et al. 1997).

The source went into a very high X-ray luminosity state in early 1996 and was observed on several occasions by the Pointed Proportional Counters (PPCs) of the Indian X-ray Astronomy Experiment (IXAE) (Agrawal et al. 1997; Paul et al. 1997a), the Proportional Counter Array (PCA) and the All Sky Monitor (ASM) of the Rossi X-ray Timing Explorer (RXTE) (Bradt 1996). The X-ray intensity was found to vary on a variety of time scales and the spectrum also changed during the brightness variations (Greiner et al. 1996). PPC observations of GRS 1915+105 in its low hard state in 1996 July showed intensity variations by a factor of 2 to 3 at $100-400$ ms time scale (Paul et al. 1997a;b). Strong (rms variability 9%) and narrow ($\frac{\nu}{\delta\nu} \approx 5$) Quasi Periodic Oscillations (QPOs) of varying frequency were discovered in GRS 1915+105 with the PPC observations (Agrawal et al. 1996). Intensity dependent narrow QPOs were also detected with the PCA (Morgan et al. 1997).

Several features in the observed properties of GRS 1915+105 such as the Power Density Spectra (PDS) with the QPO feature, a hard X-ray tail and the subsecond time variability, are typical characteristics of black hole binaries. The X-ray intensity is found to be more than 10^{39} erg s^{-1} for extended periods which is super-Eddington luminosity for a neutron star. Stable and narrow QPOs at a frequency of 67 Hz were observed with the PCA, and associating these to the Keplerian period of the innermost stable orbit around a black hole, the mass for a non-rotating black hole has been estimated to be 33 M$_\odot$ (Morgan et al. 1997).

The most compelling evidence for the existence of a black hole in Galactic X-ray binaries normally comes from the measured mass function which indicates that the mass of the compact object is much larger than that permitted for a neutron star. In the absence of measured binary parameters (like in the case of GRS 1915+105) phenomenological arguments are normally used, which, though compelling for a class of objects, are not conclusive enough for individual cases. This is mainly due to the fact that the accretion disk around a black hole has properties quite similar to that around a low magnetic field neutron star (Tanaka and Lewin 1995). Recent progress in the understanding of accretion onto

black holes, however, has indicated a possible way of uniquely separating the properties of accretion onto black holes and neutron stars. It is found that the black hole accretion disks are cooled by advection in their innermost parts and it has been realized that advection is one of the most fundamental features of the black hole accretion (Chakrabarti 1996; Abramowicz and Percival 1997). In this *Letter* we present a possible evidence for the direct detection of advection in GRS 1915+105. This is based on the detection of regular and persistent X-ray bursts from this source. The bursts are different in temporal structure and regularity of occurrence from the classical bursts in Low Mass X-ray Binaries (LMXB). The bursts have a slow exponential rise and sharp decay. The sharp decay, which is the most significant difference from the bursts in the neutron star sources, and the hardening of the spectrum as the burst progresses, indicate a possibility that we are observing the advection of matter into the black hole horizon. In the following sections, we describe the observations and properties of 635 regular bursts observed with the PPCs. We discuss the possibility of such a phenomena taking place in the framework of an accretion disk model with an oscillating shock front (Chakrabarti and Titarchuk 1995).

2. Observations

The observations were carried out using the 3 PPCs of the Indian X-ray Astronomy Experiment (IXAE) onboard the Indian satellite IRS-P3 launched on 1996 March 21 from India using a PSLV rocket. The principle objective of this experiment is to carry out short and long term variability studies of X-ray binaries and other variable X-ray sources. The PPCs, filled with argon-methane mixture at 800 torr pressure and working in the $2-18$ keV energy range, have a total area of 1200 cm^2 and field of view of $2.3° \times 2.3°$. The energy resolution is $\approx 22(\frac{E}{6})^{-\frac{1}{2}}\%$ at E keV with a detection efficiency of about 65% at 6 keV and 10% at 15 keV. Each PPC is a multilayer unit consisting of 54 anode cells of size 1.1 cm $\times$ 1.1 cm arranged in 3 identical layers. The end cells of each layer and all the 18 anodes of the third layer are connected together and operated as a veto layer for the top two layers which constitute the X-ray detection volume. The alternate anodes in each of the two X-ray detection layers are joined together and operated in mutual anti-coincidence to reject charged particle induced background. A star tracker onboard the IRS-P3 satellite co-aligned with the viewing axes of the proportional counters is used for pointing towards the X-ray sources. For further details of the PPCs and the observation methodology see Rao et al. (1997).

Observations with the PPCs are usually made in about 5 orbits of the satellite every day and each observation has a duration of about 20 minutes. During the observation

period of 1997 June 12 to June 29, a total of 39,300 seconds of useful exposure time was obtained on source. Data were recorded with a time resolution of 1 s during June 21−26 and 0.1 s on the rest of the days. About half of the useful exposure was obtained with 1.0 s time resolution. In the 1.0 s mode of observation, data are available for five orbits every day whereas in the 0.1 s mode usually data are available only for three orbits due to the limited size of the onboard data storage unit.

3. Results

Three types of bursts are observed during the PPC observations over the period of 1997 June 12 to 29 - (a) regular bursts, having a slow rise and sharp decay lasting for ∼ 10 s and recurring every 45 s, (b) irregular bursts of variable duration, slow rise, flat top and sharp decay, and (c) long bursts, with duration of a few tens to a few hundred seconds, followed by sharp decay. Sharp decay is a common feature of all the bursts. Regular bursts were detected during June 12−17 and again during June 22−26, the irregular bursts during June 18−21 and long bursts were detected after June 27. Representative light curves of 500 s duration obtained on different days are shown in Figure 1. All the panels in the figure have similar Y-axis scales, and the X-axis is adjusted such that a burst decay phase occurs around 250 s. A secondary peak near the end of the bursts is a common feature of all the bursts. A total of 635 regular bursts (in ∼ 28,200 s of observation), 78 irregular bursts (in 6,200 s) and 40 long bursts (in ∼ 4,900 s) have been detected. The long bursts show higher variability near the end of the burst and the burst duration is correlated to the quiescent state period just prior to the burst. Similar behavior is also reported from PCA observations carried out in 1996 June (Belloni et al. 1997a). Several irregular bursts, concurrent with the present observations on 1997 June 18 and having similar properties has also been detected in the PCA data (Belloni et al. 1997b). Taam et al. (1997) reported the detection of a series of regular bursts recurring every 60 s to 100 s during 5.5 hours of PCA observation on 1996 October 15. The present observations show that the regular bursts are stable for several days. We discuss the properties of these bursts below.

The regular bursts detected during June 12−17 and again during June 22−26, have a peak intensity of about 3 to 5 times the quiescent intensity. In all the bursts, a dip is present just before the decay of the burst. But the most remarkable feature of our observations is the persistence of the regular bursts for a few days with similar shape, structure and period. The separation between the successive bursts shows a random walk in time instead of any regular pattern. Time separation between the bursts averaged over one day is found to be in the range of 40 s to 52 s, with a large scatter. The distribution of burst interval for each

day fits well with a Gaussian, with a tail on the higher side, having a mean in the range of 40 s to 50 s and $\sigma \sim 3$ s.

Individual bursts are well fitted with a profile which is a sum of two bursts with exponential rise and very fast linear decay along with a constant emission. A typical burst profile is shown in Figure 2. To improve the statistical accuracy of the data we have co-added a large number of bursts by matching the peak of the fitted profiles. The co-added burst profiles in two different energy ranges ($2-6$ keV and $6-18$ keV) are shown in the top two panels while the hardness ratio is shown in the third panel of Figure 3. The sharp features are smeared due to addition of bursts of different duration. Intensity changes are more prominent at higher energy and the energy spectrum becomes harder as the burst progresses. The burst is hardest near the end of its decay. This is a unique feature of these bursts which distinguishes them from the bursts seen in LMXBs which become softer in the decaying phase (Lewin et al. 1995).

We have calculated the possible temperature and radius distribution assuming a multi-temperature disk black-body model for the burst emission with the temperature (kT_{in}) and radius (R_{in}) of the innermost region of the accretion disk as free parameters. For this purpose, the burst count rate and the hardness ratio are obtained after subtracting the quiescent value from the observed count rates. From the spectral fitting reported by Taam et al. (1997), it is seen that during a burst the power-law component in the $2-10$ keV region changes by a factor less than 2, whereas the disk emission component changes by a factor more than 4. This indicates that the burst emission has a spectral type which is similar to the disk black-body emission. From the response matrix of the PPC detectors, the observed total count rate and hardness ratio profiles are converted to the R_{in} and kT_{in} of the innermost disk. The hardness ratio profile of only the burst component, temperature of the inner part of the disk (kT_{in}) and the inner radius of the disk (R_{in}) are shown in the three panels at the bottom of Figure 3. The data after 30 s are taken as the quiescent level and hence they are not used for the hardness ratio calculation and plotting. It can be seen from the figure that the temperature increases sharply during the burst decay phase. The radius R_{in} remains constant during most of the rising phase of the burst, but decreases sharply during the burst decay.

4. Discussion

The bursts in GRS 1915+105 are very different from the type I X-ray bursts seen in about 40 LMXBs and type II X-ray bursts in the Rapid Burster (MXB 1730−335) because of their unique feature of slow rise and fast decay. All the bursts in the LMXBs have fast

rise time of less than a second to 10 seconds and slow decay of 10 seconds to a few minutes (Lewin et al. 1995). The type I X-ray bursts are understood to be thermo-nuclear flashes caused by accretion of matter on to the neutron star surface. The type II bursts are caused by sudden infall of matter on to the neutron star due to some instability in the inner part of the disk supported by the magnetic field. The slow decay of the burst intensity represents the cooling time scale of the neutron star photosphere.

The two peculiarities of the bursts in GRS 1915+105 are the regularity with which they occur over time scale of several days, and the presence of a secondary peak in all the bursts. In the classical bursts, the spectrum is initially hard and becomes softer as the burst decays (Lewin et al. 1995). In sharp contrast, the bursts in GRS 1915+105 remain hard till the end and it is, in fact, the hardest near the end of the burst.

The ratio of luminosity in type I X-ray bursts (L_b) and the average quiescent X-ray luminosity (L_p) is $\frac{L_b}{L_p} \sim 10^{-2}$. The time-averaged type II burst luminosity is much higher, usually 0.4 to 2.2 times the average luminosity of quiescent emission (Lewin et al. 1995). The time-averaged luminosity of the regular bursts detected from GRS 1915+105 is 0.3 to 0.5 times the luminosity of the quiescent emission. This is much higher than the ratio in type I bursts (where the thermonuclear process has much smaller efficiency compared to the gravitational process) and less than the type II bursts (where the burst emission is due to gravitational energy release). The emission process involved in producing the bursts here is not likely to be thermo-nuclear because of the energetics involved. If the energy generation process is gravitational (like in type II bursts), the difference in efficiency might indicate the absence of hard surface in the compact object. A process in which the energy produced is due to gravitational potential but not all the energy is emitted as radiation, part of it being advected into the event horizon as kinetic energy of the matter, is appropriate for this source.

Taam et al. (1997) have attempted to describe the regular bursts in GRS 1915+105 in the frame work of the thermal/viscous instabilities in the accretion disks. This model is based on the fact that the inner regions of accretion disk in the standard model are unstable to thermal and surface density fluctuations (Taam and Lin 1984). Using various scaling laws for viscosity (like the viscous stress scaling as the total pressure), they solved time dependent differential equations for the inner accretion disk and found that the thermal instability manifests as short duration luminosity fluctuations or bursts. The accretion disk models which solve the inner boundary conditions and invoke the advection effects explicitly (Chakrabarti 1996; Abramowicz and Percival 1997), however, find that the thermal/viscous instabilities are removed completely by the addition of advection effects. Hence we attempt to explain the regular bursts in GRS 1915+105 in terms of advection effects in an accretion

disk around a black hole.

The regular bursts observed in GRS 1915+105 can be due to periodic infall of matter onto a black hole from an oscillating shock front. In the black hole accretion disk model of Chakrabarti and Titarchuk (1995), the disk has two components, an equatorial Keplerian disk and a sub-Keplerian component just above and below the Keplerian disk. The sub-Keplerian component of the disk experiences a shock due to centrifugal barrier and if the cooling time scale of the post-shock halo matches with the material infall time scale, oscillations can set in (Molteni et al. 1996). If the matter accreted from the companion has high angular momentum and low viscosity, the shock front can be far away from the black hole and oscillation period can be very large. The oscillation period (t_{osc}) of the shock depends on the mass of the black hole (M) and the radius at which the shock is formed (R), and is given by $t_{osc} = 12.5 \left(\frac{R}{1000 \ r_g}\right)^{\frac{3}{2}} \left(\frac{M}{10 \ M_\odot}\right)$ s where r_g is the Schwartzchild radius (Chakrabarti 1997). For a 30 $M_\odot$ black hole, if the oscillation period is 50 s, the shock front should be at a radius of 1200 r_g.

It is possible that at some particular phase of this oscillation the piled up matter behind the shock falls catastrophically onto the black hole and a burst is produced. As the matter goes in, temperature increases producing large X-ray intensity. The free fall time scale, from the shock front at a distance R, to the black hole is $t_{free} = 2.1 \left(\frac{R}{1000 \ r_g}\right)^{\frac{3}{2}} \left(\frac{M}{10 \ M_\odot}\right)$ s. Comparing t_{osc} and t_{free} we find that for t_{osc} to be about 50 s, the free fall time should be 8.4 s in fair agreement with the rise time of the bursts. The burst is suddenly terminated as the matter goes behind the event horizon of the black hole. In this scenario, as the burst progresses, the temperature of the infalling matter increases, giving rise to the observed spectral hardening. In the same model, the irregular and long bursts can be produced, if the accreted matter has somewhat larger angular momentum, so that a momentary disk is formed before it is advected.

5.   Conclusion

In conclusion, we have presented observations of a unique type of X-ray bursts in the galactic superluminal transient source GRS 1915+105. This is the only black hole candidate in which regular bursts are observed. The observed bursts are very different compared to the classical bursts in the LMXBs both in terms of temporal structure and spectral evolution. We propose that the sharp decay of the bursts and the hardening of the spectrum near the end of the decay indicate disappearance of accreted matter into the black hole horizon.

Since the advection is one of the fundamental features of accretion onto black holes, such temperature profiles during outbursts in black hole candidates should be commonly observable and provide an observational test to distinguish the black hole binaries from the neutron star binaries. For example, the co-added shots in the well known Galactic black hole candidate Cygnus X-1 shows spectral hardening after the burst peak (Negoro et al. 1994), which possibly indicates advection effect. A quantitative fitting of profile of similar bursts using the refined accretion disk models and investigating similar effects in other black hole candidate sources should eventually provide an unique distinguishing feature of accretion onto the black holes.

REFERENCES

Abramowicz, M. A., & Percival, M. J. 1997, Class. Quantum Gravity, 14, 2003

Agrawal, P. C., et al. 1996, IAU Circ. 6488

Agrawal, P. C., et al. 1997, Journal of the Korean Astronomical Society, 29, S429

Belloni, T., et al. 1997a, ApJ 479, L145

Belloni, T., et al. 1997b, ApJ *Letters* (in press)

Brad, H. 1996, Proceedings of 5th International Workshop on Data Analysis in Astronomy, Erice, Italy, eds. Scarsi, L. & Maccarone, C. World Scientific Publ. Co.

Castro-Tirado, A. J., et al. 1994, ApJS, 92, 469

Chakrabarti, S. K., & Titarchuk, L. G. 1995 ApJ, 455, 623

Chakrabarti, S. K. 1996, ApJ, 464, 664

Chakrabarti, S. K. 1997, private communication

Foster, R. S., et al. 1996, ApJ, 467, L81

Greiner, J., Morgan, E. H., & Remillard, R. A. 1996, ApJ, 473, L107

Harmon, B. A., et al. 1997 ApJ, 477, L85

Lewin, W. H. G., Jan Van Paradijs, & Taam, R. E. in X-ray Binaries, eds. Lewin., W. H. G., Jan Van Paradijs, & van den Heuvel, Cambridge: Cambridge University Press, p. 175-232, 1995

Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46

Molteni, D., Sponholz, H., & Chakrabarti, S. K. 1996, ApJ, 457, 805

Morgan, E. H., Remillard, R. A., & Greiner, J. 1997, ApJ, 482, 993

Negoro, H., Miyamoto, S., & Kitamoto, S. 1994, ApJ 423, L127

Paul, B., et al. 1997a, A & A, 320, L37

Paul, B., et al. 1997b, A & A Supplement Series (in press)

Rao, A. R., et al. 1997, A & A, (in press)

Taam, R. E., Chen, X., & Swank, J. H. 1997, ApJ, 485, L83

Taam, R. E., & Lin, D. N. C. 1984, ApJ, 287, 761

Tanaka, Y., & Lewin, W. H. G. in X-ray Binaries, eds. Lewin., W. H. G., Jan Van Paradijs, & van den Heuvel, Cambridge: Cambridge University Press, p. 166, 1995
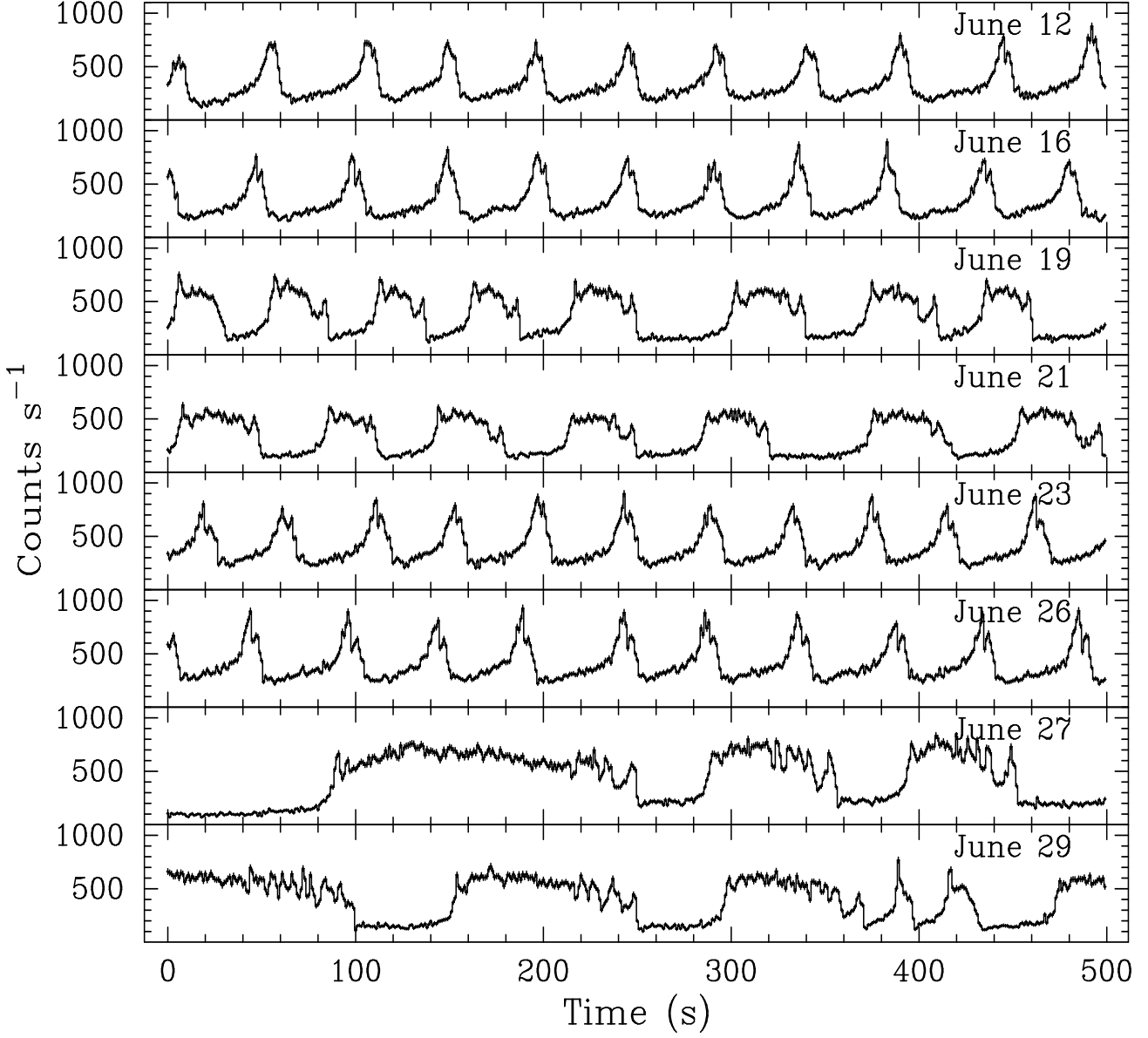
Fig. 1.— The regular (first, second, fifth and sixth panel from the top), irregular (third and fourth) and long (seventh and eighth panel) bursts observed in GRS 1915+105 with one of the PPCs. Date of each observation is given in the respective panels.
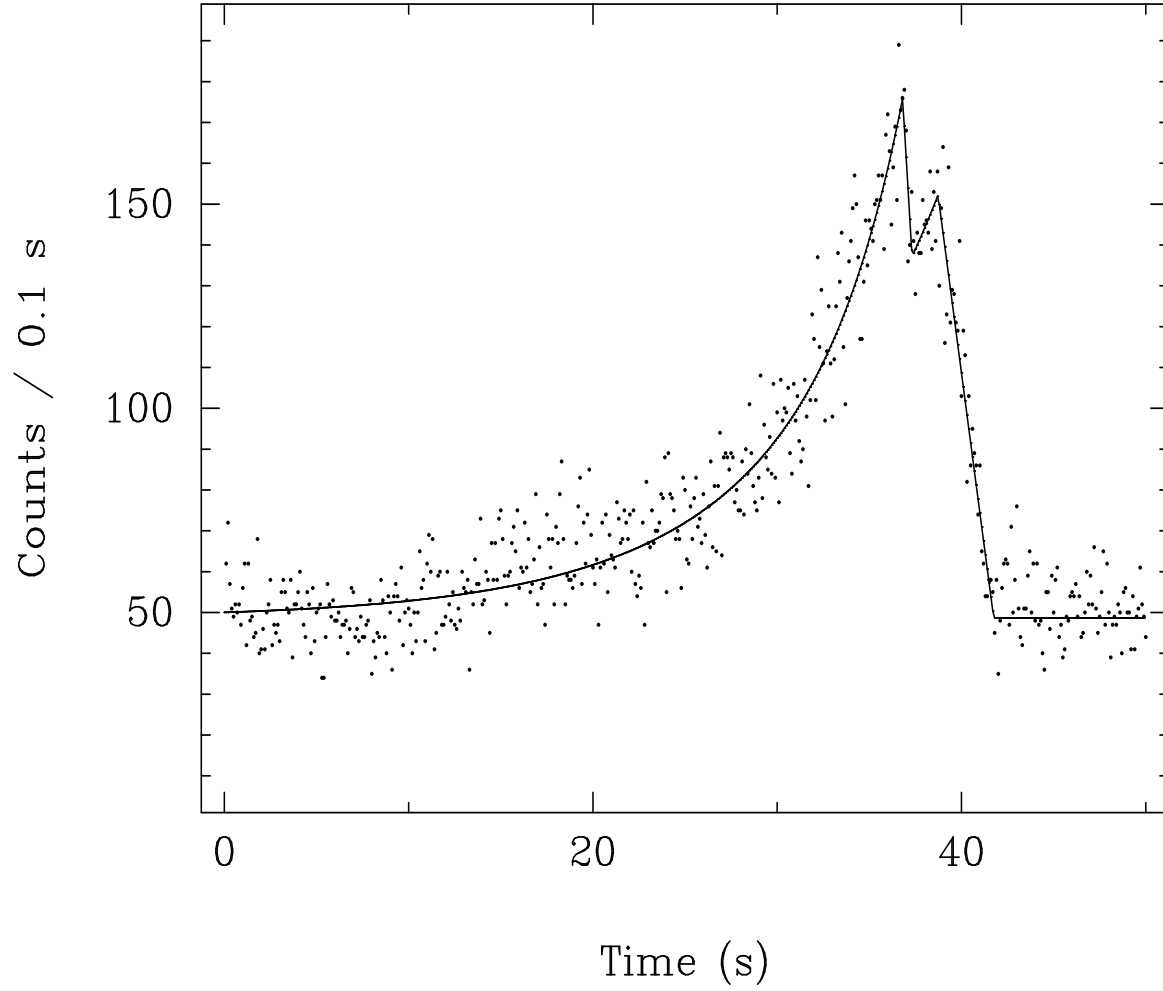
Fig. 2.— Profile of a regular burst is shown along with the best fit model (continuous line) consisting of two burst with exponential rise and linear decay, and a constant intensity.
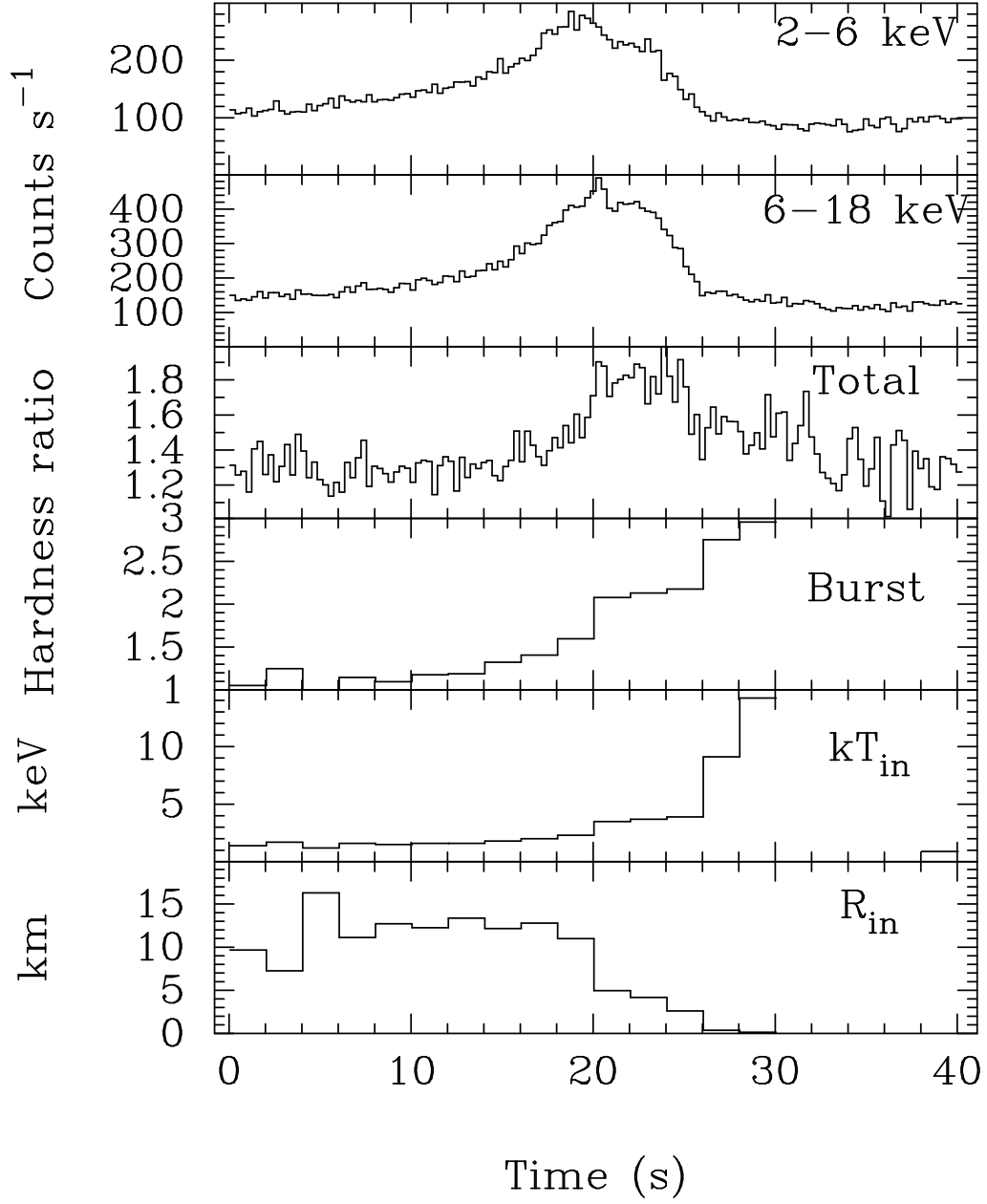
Fig. 3.— The burst profile in two different energy ranges are shown in the top two panels. The middle two panels show the hardness ratio of the total light-curve and hardness ratio of only the burst. The quiescent intensity (30−40 s time range in the figure) was subtracted from the light curves and the resultant profiles were taken to generate the hardness ratio of only the bursting component. This is why the fourth panel extends only upto 30 s. The temperature (kT_{in}) and radius (R_{in}) of the innermost disk of an assumed multi-temperature disk emission, are plotted in the bottom two panels.